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Infrared observations of the recurrent nova T Pyxidis: ancient dust basks in the warm glow of the 2011 outburst*

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ABSTRACT

We present *Spitzer Space Telescope* and *Herschel Space Observatory* infrared observations of the recurrent nova T Pyx during its 2011 eruption, complemented by ground-base optical-infrared photometry. We find that the eruption has heated dust in the pre-existing nebulosity associated with T Pyx. This is most likely interstellar dust swept up by T Pyx – either during previous eruptions or by a wind – rather than the accumulation of dust produced during eruptions.

Key words: circumstellar matter – stars: individual, T Pyx – novae, cataclysmic variables – infrared: stars – ISM: general

1 INTRODUCTION

Nova eruptions occur as a result of a thermonuclear runaway (TNR) on the surface of a white dwarf (WD) in a semi-detached binary system. In classical novae (CNe) the secondary star is normally a red dwarf. Mass is transferred from the secondary through the inner Lagrangian point onto the surface of the WD via an accretion disc. The degenerate layer of accreted material is compressed and heated, and a TNR occurs (Starrfield, Iliadis & Hix 2008). Consequently $\sim 10^{-4}\,M_\odot$ of material, enriched in CNO (and other metals), is ejected at a few hundred to a few thousand $km\,s^{-1}$ (Gehrz et al. 1998; Bode & Evans 2008) in a CN eruption. Once the eruption has subsided the mass transfer resumes, and in time ($\sim 10^4 - 10^5$ years) another nova eruption occurs. A CN system therefore undergoes many eruptions during its lifetime: nova eruptions recur.

Recurrent novae (RN) undergo the same evolution; however eruptions recur on less than a human timescale, typically 10–20 years (e.g. Evans et al. 2008, for a recent review). They seem to divide into 3 sub-classes (Anupama 2008). These are the "U Sco" class (with short orbital periods and spectral evolution similar to that of the 'He/N' class of CNe; see Williams 1992); the "RS Oph" class (with long orbital periods), and the "T Pyx" class (also with short orbital periods and spectral evolution that evolves from 'He/N' to 'Fe II'). The T Pyx class resembles the CNe in terms of the nature of the binary system and the spectral evolution during eruption.

We present here infrared (IR) space- and ground-based IR

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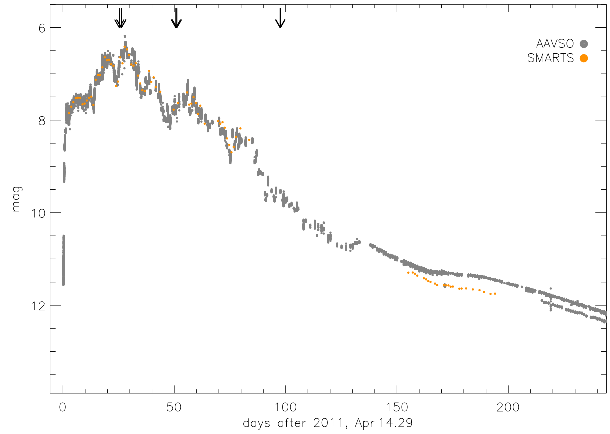

Figure 1. The visual (V-band) light curve of T Pyx during the 2011 eruption, based on observations in the AAVSO (black) and SMARTS (orange) databases. The apparent offset for $t \gtrsim 150$ days arises because AAVSO data have been corrected for a differential airmass effect, caused by most of the flux being in strong discrete lines rather than being smoothly distributed in the continuum (Oksanen & Schaefer 2011). The times of the IR observations discussed in this paper are indicated by the arrows.

spectrophotometry, as well as optical broadband photometry, of the RN T Pyx following its 2011 eruption.

2 T Pyx

2.1 The system

T Pyx has undergone recorded nova eruptions in 1890, 1902, 1920, 1944 and 1966; in fact, it was the first nova identified as a recurrent. The T Pyx binary has an orbital period of 1.83 h (Uthas, Knigge & Steeghs 2010). The mass ratio is determined to be 0.20 ± 0.03 by Uthas et al. (2010), who estimate the WD and cool companion mass to be $0.7\,M_\odot$ and $0.14\,M_\odot$ respectively. The former is rather low for either a RN or a CN and if the WD mass is a more plausible $\geqslant 1\,M_\odot$, the secondary mass has to be $\geqslant 0.2\,M_\odot$; in the discussion below we assume $1.2\,M_\odot$ for the WD mass in T Pyx (Anupama 2008; Schaefer et al. 2010). Uthas et al. (2010) determine that the inclination of the binary is $\sim 10^\circ$, i.e. nearly face-on. Possible evolutionary scenarios for T Pyx have been discussed by Schaefer, Pagnotta & Shara (2010) and Uthas et al. (2010). In T Pyx, as in a CN, the nova explosion occurs on the surface of the WD following a TNR in a layer of degenerate material accreted from the secondary.

T Pyx is unusual amongst RNe in that it lies at the centre of a nova-like shell with diameter $\sim 15''$ (Dürbeck & Seitter 1979, see also Schaefer et al. 2010). A detailed study of knots in the nebula (Schaefer et al. 2010) has revealed complex interactions between material ejected in earlier eruptions. Schaefer et al. find that there has been no significant deceleration of the knots and, based on the angular expansion rate of the knots, deduce that they were ejected by a CN-type eruption close to the year 1866. They find knots ejected in 1866 that have "turned on" since 1995, and suggest that these knots are powered by shocks caused by collisions with fast ejecta from more recent RN eruptions.

Selvelli et al. (2008) estimated the distance of T Pyx as 3500 ± 350 pc. Schaefer et al. (2010) summarise several estimates of the interstellar reddening, and conclude that $E(B-V) = 0.25 \pm 0.02$. On the basis of observations carried out in the aftermath of the 2011 eruption (see below), Shore et al. (2011) propose a distance $\geqslant 4.5$ kpc and reddening $E(B-V) = 0.50 \pm 0.10$. We shall use $D = 4$ kpc and $E(B-V) = 0.4$ here, although the precise values do not affect our main conclusions (e.g., reddening has negligible effect at the IR wavelengths of interest here).

2.2 The 2011 eruption

T Pyx was discovered to be in outburst on 2011 April 14.29 UT (MJD55665.29) by M. Linnolt (see Waagen 2011). The 2011 eruption, almost 50 years after its last, was well overdue; this delay led Schaefer et al. (2010) to speculate that T Pyx was entering "hibernation", and that there would be no further eruptions for $\sim 10^6$ years. Possible reasons for this inter-outburst behaviour are discussed by Schaefer et al. (2011), who also provide a comprehensive discussion of the early visual light curve.

Spectroscopic observations by Shore et al. (2011) revealed expansion velocities $\sim 2\,500$ km s^{-1} during the early stages of the eruption. They deduce an ejected mass of $10^{-5}\,f\,M_\odot$, where f is the filling factor for the ejected material. VLTI and Mount Wilson CHARA IR observations (Chesneau et al. 2011) provide evidence for a bi-polar ejection that is essentially face-on, consistent with the low inclination of the system (Uthas et al. 2010).

Swift (Gehrels 2004) observations started some 7.5 hours after discovery, and revealed a soft X-ray source (Kuulkers et al. 2011a), but between days 12–109 (which covers the IR data reported here) the X-ray source was very weak (Osborne et al. 2011). Subsequently (from day 142), the X-ray emission was bright and variable (Kuulkers et al. 2011b).

The visual (V-band) light curve during the 2011 eruption is shown in Fig. 1. The UVOT instrument on *Swift* showed that the ultraviolet flux at 2246Å peaked some 25 days later than the visual flux (Osborne et al. 2011).

3 OBSERVATIONS

Broadband photometric IR observations were carried out at the Infrared Telescope on Mount Abu (Deshpande 1995; Anandarao & Chakraborty 2010), and as Directors' Discretionary Time on the *Spitzer Space Telescope* (Werner et al. 2004; Gehrz et al. 2007) and the *Herschel Space Observatory* (Pilbratt 2003; Pilbratt et al. 2010); these data were supplemented, as closely in time as possible, by optical and IR photometry from the AAVSO[1] and SMARTS[2] archives.

3.1 Mt. Abu

Near IR photometry of T Pyx in the JHK bands was carried out with the Mt. Abu 1.2-m telescope using the 256×256 HgCdTe NICMOS3 array of the Near-Infrared Imager/Spectrometer (see Banerjee & Ashok 2011). Observations of both T Pyx and a comparison star (SAO 177754: $J = 7.082 \pm 0.029$, $H = 7.070 \pm 0.061$, $K = 6.963 \pm 0.018$) were made at 5 dithered positions in each of the J, H and K bands. The dithered images were combined to produce a median sky frame, with dark counts included, which was subsequently subtracted from the object frames.

[1] http://www.aavso.org/
[2] http://www.astro.sunysb.edu/fwalter/SMARTS/NovaAtlas/

Table 1. Optical and infrared fluxes for T Pyx. Ground-based data are given both in magnitudes and, immediately beneath, in mJy; IRAC and PACS data are in mJy. All mJy values are in bold font. t is the time (in days) since eruption. Numbers in brackets are uncertainties in last figure(s) of quoted fluxes. Horizontal lines separate quasi-contemporaneous data obtained on different dates.

UT Date				Optical				Ground-based Infrared			IRAC (mJy)		PACS (mJy)		
YYYY-MM-DD.DD	MJD	t (d)	Facility*	B	V	R	I	J	H	K	3.6 μm	4.5 μm	70 μm	100 μm	130 μm
2011-05-09.52	55690.52	25.23	S	7.47(1)	7.18(1)	6.56(1)	6.26(1)	–	–	4.97(1)	–	–	–	–	–
				4 390	**4 928**	**6 750**	**7 050**	–	–	**6 480**	–	–	–	–	–
2011-05-09.64	55690.64	25.35	M	–	–	–	–	5.53(2)	5.28(2)	4.96(3)	–	–	–	–	–
				–	–	–	–	**9 391**	**7 874**	**6 536**	–	–	–	–	–
2011-05-10.50	55691.50	26.21	A	7.03	6.60	6.24	–	–	–	–	–	–	–	–	–
				6 583	**8 407**	**9 064**	–	–	–	–	–	–	–	–	–
2011-05-10.53	55691.53	26.24	H	–	–	–	–	–	–	–	–	–	**255(44)**	**185(46)**	**137(39)**
2011-05-10.53	55691.53	26.24	S	7.09(1)	6.77(1)	–	5.87(1)	–	–	–	–	–	–	–	–
				6 229	**7 189**	–	**10 097**	–	–	–	–	–	–	–	–
2011-05-11.53	55692.53	27.24	S	7.10(1)	6.78(1)	–	5.89(1)	4.94(1)	5.09(1)	4.77(1)	–	–	–	–	–
				6 172	**7 123**	–	**9 912**	**16 110**	**9 414**	**7 822**	–	–	–	–	–
2011-06-04.51	55716.51	51.22	I	–	–	–	–	–	–	–	**2 048(10)**	**2 000(10)**			
2011-06-04.96	55716.96	51.67	S	7.87(1)	7.63(1)	7.07(2)	6.72(1)	5.86(1)	5.99(1)	5.47(1)	–	–	–	–	–
				3 037	**3 256**	**4 220**	**4 615**	**6 923**	**4 094**	**4 098**	–	–	–	–	–
2011-07-20.84	55762.84	97.55	I	–	–	–	–	–	–	–	**310(10)**	**422(10)**	–	–	–
2011-07-20.96	55762.96	97.67	A	–	9.58	–	–	–	–	–	–	–	–	–	–
				–	**540**	–	–	–	–	–	–	–	–	–	–

*A = AAVSO; H = *Herschel* PACS; I = *Spitzer* IRAC; M = Mt Abu; S = SMARTS.

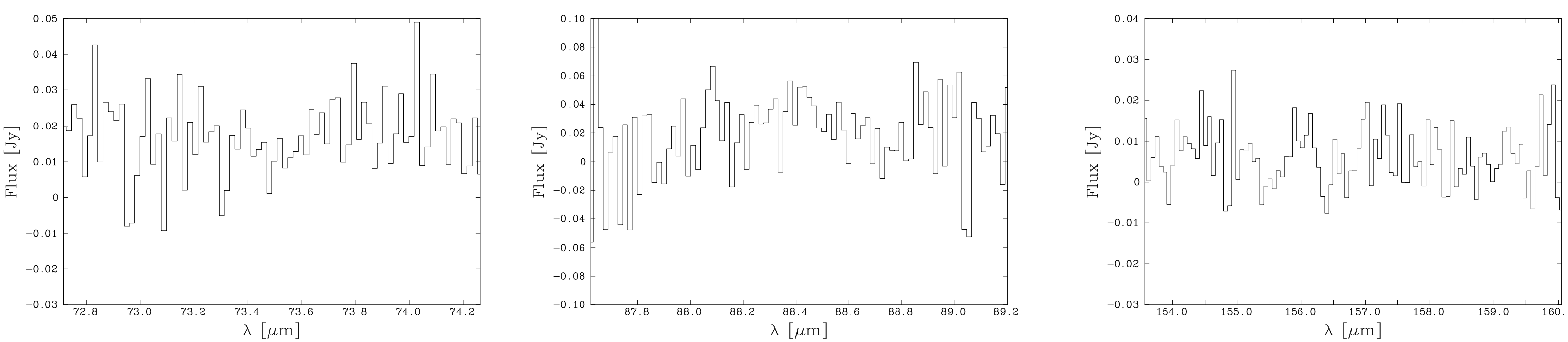

Figure 2. Three representative PACS spectra in each of the PACS photometry bands.

Aperture photometry of the sky-subtracted frames was done using IRAF to yield the JHK magnitudes given in Table 1; the magnitudes were converted to Jy using standard zero magnitude fluxes in Cox (2000). Detailed results of the near-IR studies of T Pyx from Mt. Abu will be presented elsewhere.

3.2 *Spitzer Space Telescope*

T Pyx was observed as a target of opportunity (ToO) target using a Director's Discretionary Time allocation (PID: 70260) with the Infrared Array Camera (IRAC; Fazio et al. 2004) on the *Spitzer Space Telescope* (Werner et al. 2004) at wavelengths 3.6 μm and 4.5 μm, on two occasions as detailed in Table 1. The observations were carried out in full array mode, and consisted of 9-point random, medium scale dither patterns. The frame time was 0.4 s and the on-source integration time was 3.6 s per pointing. The data were reduced using MOPEX (MOPEX 2011).

3.3 *Herschel Space Observatory*

T Pyx was observed with the Photodetector Array Camera and Spectrometer instrument (PACS; Poglitsch et al. 2010) on the *Herschel Space Observatory* (Pilbratt et al. 2010). Photometry with PACS was obtained in Line Scan mode; the area covered was typically $315'' \times 237''$ and the on-source integration time was 110 s. Spectroscopy was also obtained using PACS in Line Spectroscopy mode, to cover the lines H I (11–10) 52.5 μm, [N III] 57.32 μm, [O III] 51.80 μm, H I (15-13) 61.9 μm, [O I] 63.18 μm, [N IV] 69.40 μm, [O V] 73.5 μm, [N II] 76.50 μm, [O III] 88.36 μm and [N IV] 158.5 μm. Integration times ranged from 2160 s to 3072 s on-source. All the PACS data were reduced using HIPE version 7.0 (Ott 2010).

Fluxes in the imaging observations were measured using an object aperture of $48''$ and the background was measured typically in an annulus of $96''$ (inner) and $144''$ (outer) diameter. T Pyx was securely deteced by PACS in Photometry mode; the fluxes are given in Table 1. Apart from [N III] 57.32 μm (which we will discuss elsewhere), none of the above lines were detected in spectroscopy mode in the *Herschel* aperture, to 3σ limits of typically $\sim$ 100 mJy in all three bands (see Fig. 2). The [N III] line is at the edge of the 70 μm band and will not contribute significantly to the observed flux.

We note that T Pyx is unresolved in both IRAC and PACS images. All the data are summarised in Table 1.

4 RESULTS AND DISCUSSION

For wavelengths $\lesssim 2.2\,\mu$m the spectral energy distribution (SED) of T Pyx resembles a black body with temperature 9 000 K. There is a clear excess at long wavelengths (see Fig. 3) that appears in the *Herschel Space Observatory* PACS data. While there are several fine structure lines that may contribute to the broadband PACS fluxes, our PACS spectroscopic observations show that emission lines can not have contributed to the observed PACS fluxes.

We show below that the far-IR SED is consistent with emission at ~ 45 K and we conclude that the far-IR emission we see is due to cool dust. Newly formed dust would have a temperature of several hundreds of degrees K so soon after the eruption (e.g., Evans et al. 2005), and would be evident in near-IR ($\lesssim 5\,\mu$m) spectra obtained throughout the early phase of the eruption (Woodward et al., in preparation). Furthermore, moving at $\sim$ 2 500 km s^{-1}, the 2011 ejecta would not reach a distance from the central star commensurate with the low dust temperature for $\gtrsim 100$ years after outburst. This rules out the formation of the cool dust in the material ejected in the 2011 eruption.

The visual light curves of RNe tend to be replicated from outburst to outburst (Schaefer 2010); T Pyx is no exception, and there is no evidence for extinction events in the light curve that would be associated with dust formation during the eruptions of T Pyx. The lack of dust formation is very likely in the case of RNe like RS Oph (in which the ejected material runs into and shocks the stellar wind; Evans et al. 2007a). However we take a more cautious approach in the case of T Pyx, particularly as the T Pyx class of RNe resemble CNe, many of which are known dust-producers. We therefore do not rule out the possibility that dust might have formed in the ejecta of previous RN eruptions (even if it did not do so in the 2011 eruption).

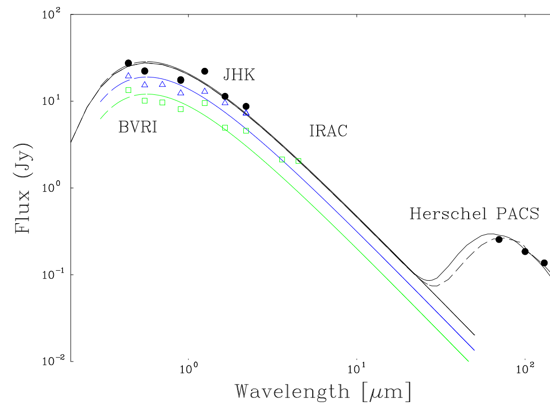

Figure 3. Spectral energy distribution of T Pyx; data are dereddened by $E(B-V) = 0.4$. The solid and broken black curves are DUSTY fits, with Sil and AmC grains respectively, to the $BVRI$, JHK and PACS data for MJD 55691.5 (2011 May 10.53 UT; filled circles). The other curves are 9 000 K blackbody fits to $BVRI$ and IRAC data for MJD 55690.5 (2011 May 9.52; triangles) and MJD 55716.96 (2011 June 4.96 UT; squares). See text for details.

We explore the origin of the dust evident in emission at $\lambda \gtrsim 30$ μm (Fig. 3) in terms of (i) dust ejected in previous T Pyx eruptions and (ii) interstellar dust swept up by ejecta, or by winds originating in the T Pyx system (e.g. Knigge, King & Patterson 2000). We consider two cases: (a) amorphous carbon (AmC) grains of radius $a = 0.2\,\mu$m, such as condense in CN winds (see e.g. Evans et al. 1997, 2005; Gehrz et al. 1998; Evans & Rawlings 2008) and (b) 0.1 μm silicate (Sil) grains. In case (a) the grains represent dust formed in previous eruptions and accumulated in the environment of T Pyx, while case (b) represents swept-up interstellar dust.

We have modelled the SED using the DUSTY code (Ivezić & Elitzur 1995), using a 9 000 K blackbody at the Eddington luminosity for a 1.2 M$_\odot$ WD (Schaefer et al. 2010) as the input source (see above); we note that the X-ray emission at this time was weak (Osborne et al. 2011) and we are therefore justified in not including any other sources (especially hot sources) of dust heating in our modelling. We assume a geometrically thin dust shell and take optical constants for Sil grains from Draine & Lee (1984), and from Hanner (1988) for AmC.

We find that, in both AmC and Sil cases the dust temperature at the inner boundary of the dust shell is 45 ± 5 K, significantly higher than that of dust in the interstellar medium ($\sim$ 20 K; Cox 2000); we conclude therefore that the dust is indeed associated with T Pyx. We further find that the SED is well fitted by an optically thin dust shell (optical depth $\tau_V \simeq 1.0[\pm 0.2] \times 10^{-4}$ at V for AmC, $\tau_V \simeq 2.2[\pm 0.3] \times 10^{-4}$ for Sil). The dust mass is $\sim 8.3 \times 10^{-5}$ M$_\odot$ (AmC) or $\sim 2.1 \times 10^{-5}$ M$_\odot$ (Sil); see Fig. 3 and Table 2 for other parameters). For a thin shell with inner radius r_1 the dust mass scales as $r_1^2\tau$, and the value of r_1 is fixed by the assumed luminosity of the central source, the dust temperature at the inner boundary and the grain material. The main source of uncertainty is in τ, and so the uncertainty in the dust mass $\delta M_{\rm dust}$ is given by $\delta M_{\rm dust}/M_{\rm dust} \simeq \delta\tau/\tau$. Table 2 summarizes the best-fit DUSTY model parameters.

While the optical depth and temperature of the dust shell are reasonably well constrained by the SED, the data are inadequate to provide any information about grain size or composition. However the deduced angular diameter θ of the dust shell is, for the Sil case, $\simeq 33''$, comparable with the dimensions of the optical nebulosity associated with T Pyx (and less than the aperture used to measure the *Herschel* fluxes; see above). The corresponding value for AmC is substantially greater than this, $\sim 78''$, and

Table 2. Parameters for DUSTY fits for a 1.2 $M_\odot$ WD; θ is the angular diameter corresponding to the diameter $2r_1$ of the dust shell. In both cases a dust shell with thickness $0.2r_1$ has been assumed. See text for details and for explanation of scaled mass.

Dust type	T (K)	a (μm)	r_1 (m)	θ (arcsec)	τ_V	Dust mass ($M_\odot$)	Scaled mass ($M_\odot$)
AmC	45	0.2	2.3×10^{16}	78	1.0×10^{-4}	8.3×10^{-5}	
Sil	45	0.1	1.0×10^{16}	33	2.2×10^{-4}	2.1×10^{-5}	6.2×10^{-4}

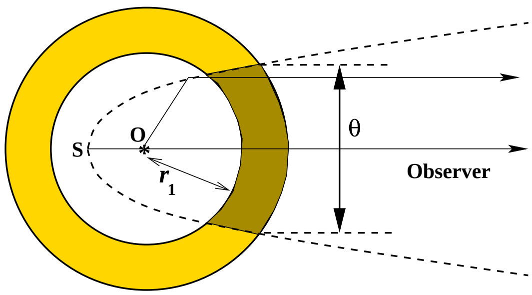

Figure 4. Geometry of IR echo. Star at O "switches on" at time $t = 0$ and illuminates dust shell (shaded); locus of constant light travel time at time t after eruption is parabola (dotted line) with focus at O and semi-latus rectum OS $= ct/2$. From the point of view of a distant observer only the hatched area is perceived to be illuminated; the observed diameter is labelled by θ.

significantly greater than the dimensions of the nebulosity; we restrict the remainder of the discussion to the Sil case.

We should inject a cautionary note in that the inner radius of the dust shell as deduced from the DUSTY modelling is $r_1 \simeq 1.0 \times 10^{16}$ m, or $\sim$ 390 light days. In view of the fact that T Pyx is highly variable, light-travel times are likely to be important (Bode & Evans 1979, see also Fig. 4) but these are not built into DUSTY. It can be shown that the angular diameter of the heated region as seen by an infinitely distant observer, at $t = 26.24$ days (the time of the PACS observation) and for the above r_1, is

$$\theta = \frac{2ct}{D} \sqrt{\left(\frac{2r_1}{ct} - 1\right)} \simeq 12''\!.2 \; ;$$

this is somewhat less than the "full" angular diameter of the dust shell ($\sim 33''$) and of the optical nebulosity ($\sim 15''$).

Also, if the (geometrically thin) dust shell is spherically symmetric it can be shown that only a fraction $ct/2r_1$ of the dust shell is perceived by the observer to be illuminated (i.e., heated); at $t = 26.24$ days this fraction is 3.4% for Sil grains. DUSTY models of the cool dust emission yield a Sil dust mass of $2.1 \times 10^{-5}\,M_\odot$ (Table 2); however, only 3.4% of the total dust mass is actually perceived to be illuminated at this epoch. Thus a lower limit to the Sil total dust mass can be determined simply by scaling. We estimate that there is actually $\sim 6.2 \times 10^{-4}\,M_\odot$ of silicate dust present.

We can definitely rule out dust-formation in the 2011 ejecta of T Pyx because there is no near-IR evidence. In addition, the "scaled mass" of dust far exceeds that produced in a nova eruption. Indeed, if confined to a circumstellar shell of radius $\sim 5.7 \times 10^{12}$ m (the distance that ejecta moving at 2 500 km s^{-1} would travel in 26.24 days), it would have resulted in substantial extinction in the optical, and the corresponding ejected mass (assuming a gas-to-dust ratio of $\sim$ 100) would be very large. We conclude that the cool dust we see in the environment of T Pyx is either (a) condensed dust accumulated from earlier eruptions, or (b) interstellar dust that has been swept up by material ejected by T Pyx in previous eruptions or by a wind from the underlying binary. If the ejected mass determined by Shore et al. (2011), $10^{-5} f\,M_\odot$, is typical of previous eruptions the dust-to-gas ratio is unfeasibly large. If the dust we see is dust condensed in previous eruptions it must be the accumulation of at least ~ 60 eruptions (as $f \leqslant 1$, and not all eruptions will have produced dust).

The mass of interstellar dust contained in a sphere having the angular diameter of the dusty T Pyx nebula ($\sim 33''$), assuming 10^{-6} 0.1 μm silicate grains m^{-3} (Allen 1973), is expected to be $\sim 3.1 \times 10^{-5}\,M_\odot$ (the corresponding mass in the *Herschel* aperture is $\sim 9.2 \times 10^{-5}\,M_\odot$). This is of the same order as the dust mass we detect. The simplest interpretation therefore is that we are seeing the result of interstellar dust swept up by winds from T Pyx. As the dust shell will continue to be heated by the 2011 eruption for some time ($> 2r_1/c \sim 2$ years) there is ample time to plan further far-IR observations to place tighter constraints on the shell parameters deduced here.

5 CONCLUSIONS

We have presented IR observations of the RN T Pyx following its 2011 outburst. We see a cool, weak IR excess, which we argue is due to the heating of dust in the environment of T Pyx that was present before the 2011 eruption. We attribute this to interstellar dust that has been swept up by material ejected by the T Pyx system, either in the course of eruptions or a wind from the binary.

It is particularly interesting that two RNe have now been found to have dusty environments that pre-date their eruptions, although the respective circumstances are very different. While the dust around T Pyx is cool, Evans et al. (2007b) found hot silicate dust in the immediate environment of RS Oph shortly after its 2006 outburst, and in this case the dust seemed to have survived the extreme environment (hard radiation field and shock blast wave) of the 2006 eruption (see also Rushton et al, to be submitted). On the other hand there is no evidence for any dust in the environment of the RN U Sco in the near-IR (Evans et al. 2001; Banerjee et al. 2010). These three RNe represent very different facets of the RN phenomenon and indeed, each is representative of the specific classes of RN (Anupama 2008) noted in Section 1, although membership of each class is very small.

Further observations of RNe, particularly at wavelengths $\gtrsim 10\,\mu$m, would help to throw light on the environments of RNe, and hence potentially on their recent history and evolution.

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